PERSPECTIVE STUDY OF CHARMONIUM AND EXOTICS IN ANTIPRPOTON-PROTON ANNIHILATION AND PROTON-PROTON COLLSIONS

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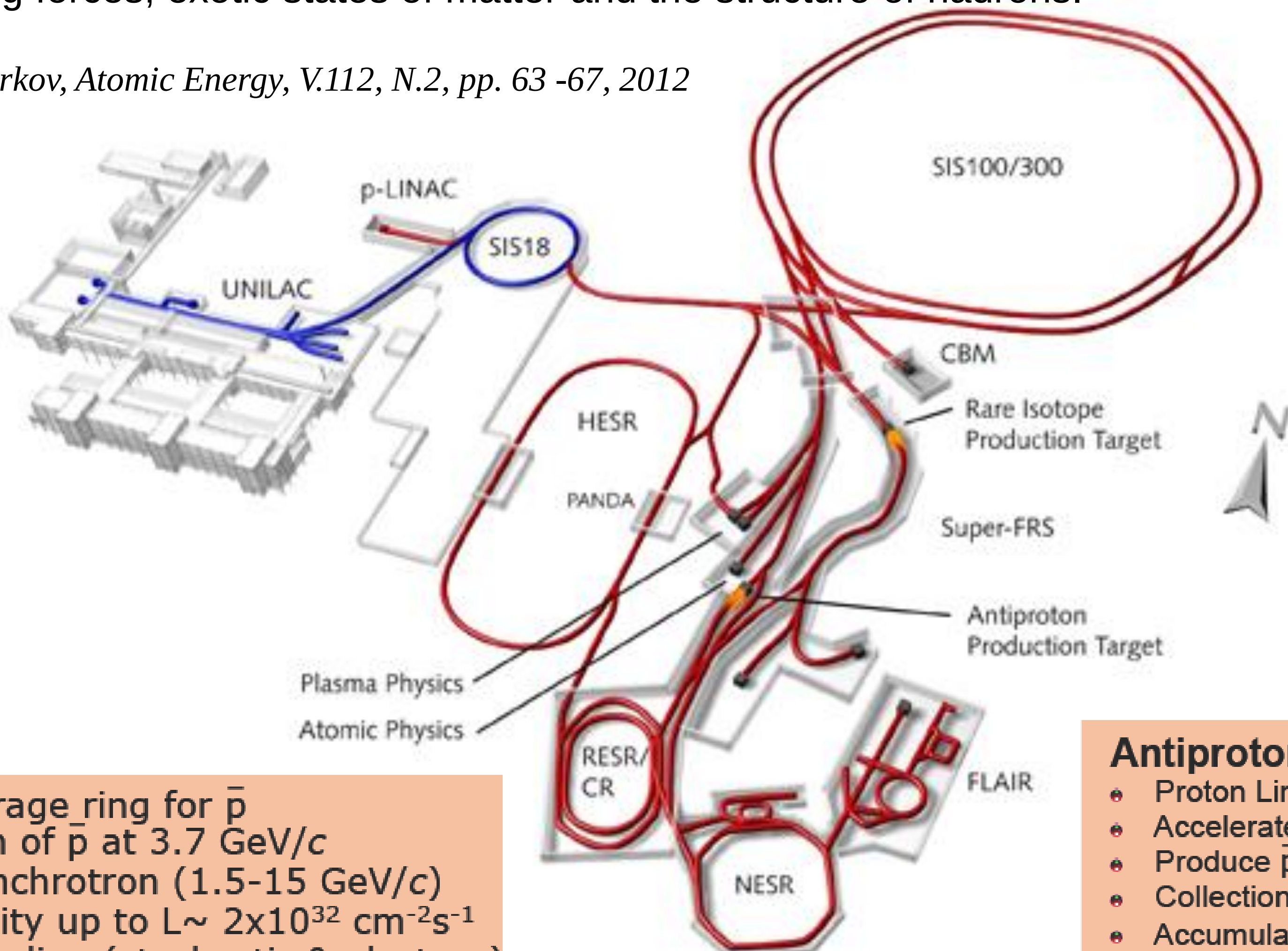
Antiprotons accumulated in the High Energy Storage Ring HESR will collide with the fixed internal hydrogen or nuclear target. High beam luminosity of an order of $2x10^{32} sm^{-2}c^{-1}$ and momentum resolution $\sigma(p)/p$ of an order of 10^{-5} are expected. The scientists from different countries intend to do fundamental research on various topics around the weak, electromagnetic and strong forces, exotic states of matter and the structure of hadrons.

* *B.Yu. Sharkov, Atomic Energy, V.112, N.2, pp. 63 -67, 2012*



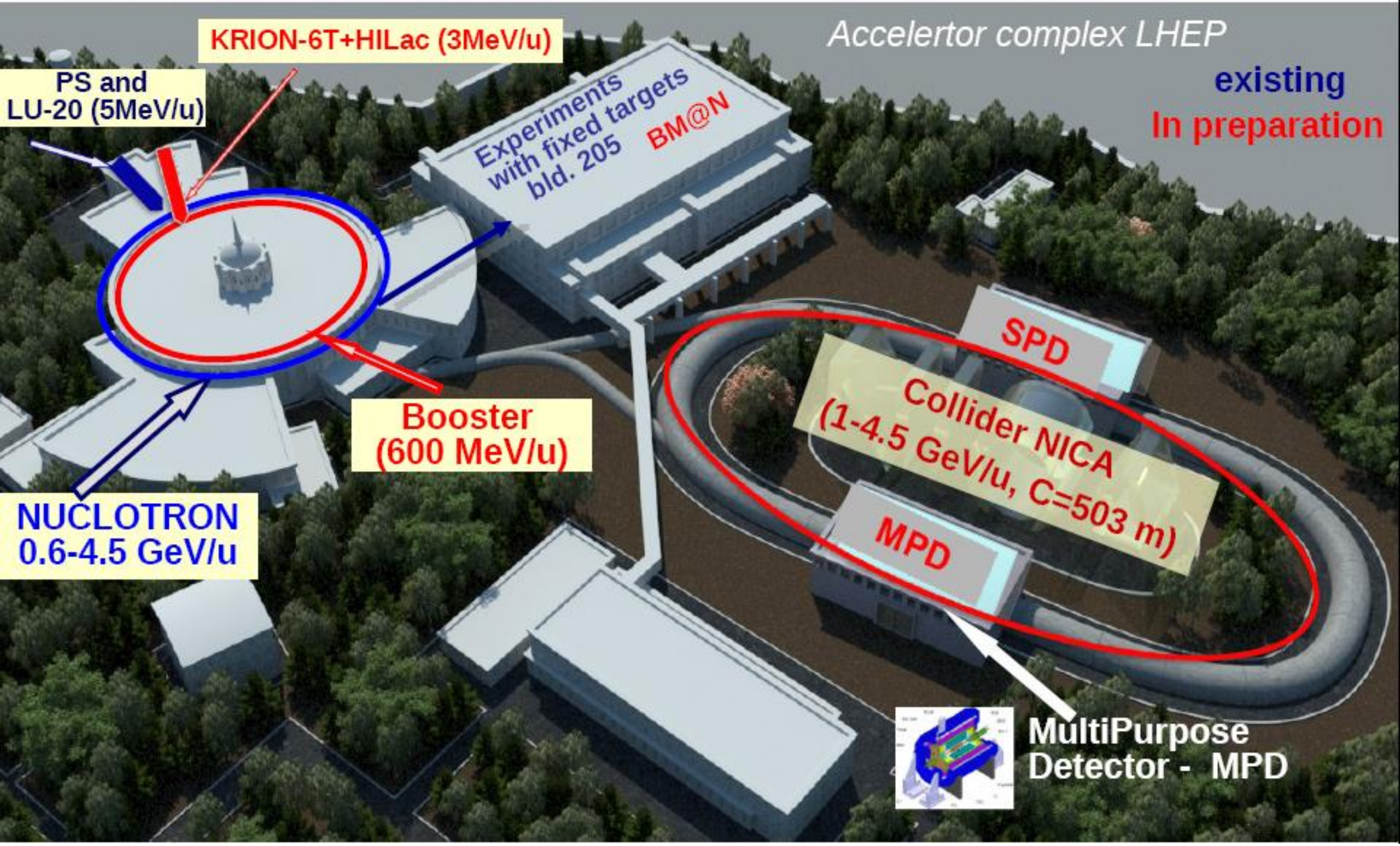
HESR: Storage ring for $\bar{p}$
- Injection of $\bar{p}$ at 3.7 GeV/*c*
- Slow synchrotron (1.5-15 GeV/*c*)
- Luminosity up to L~ $2x10^{32}$ $cm^{-2}s^{-1}$
- Beam cooling (stochastic & electron)

Antiproton production
- Proton Linac 70 MeV
- Accelerate p in SIS18 / 100
- Produce $\bar{p}$ on Cu target
- Collection in CR, fast cooling
- Accumulation in RESR
- Storage and usage in HESR

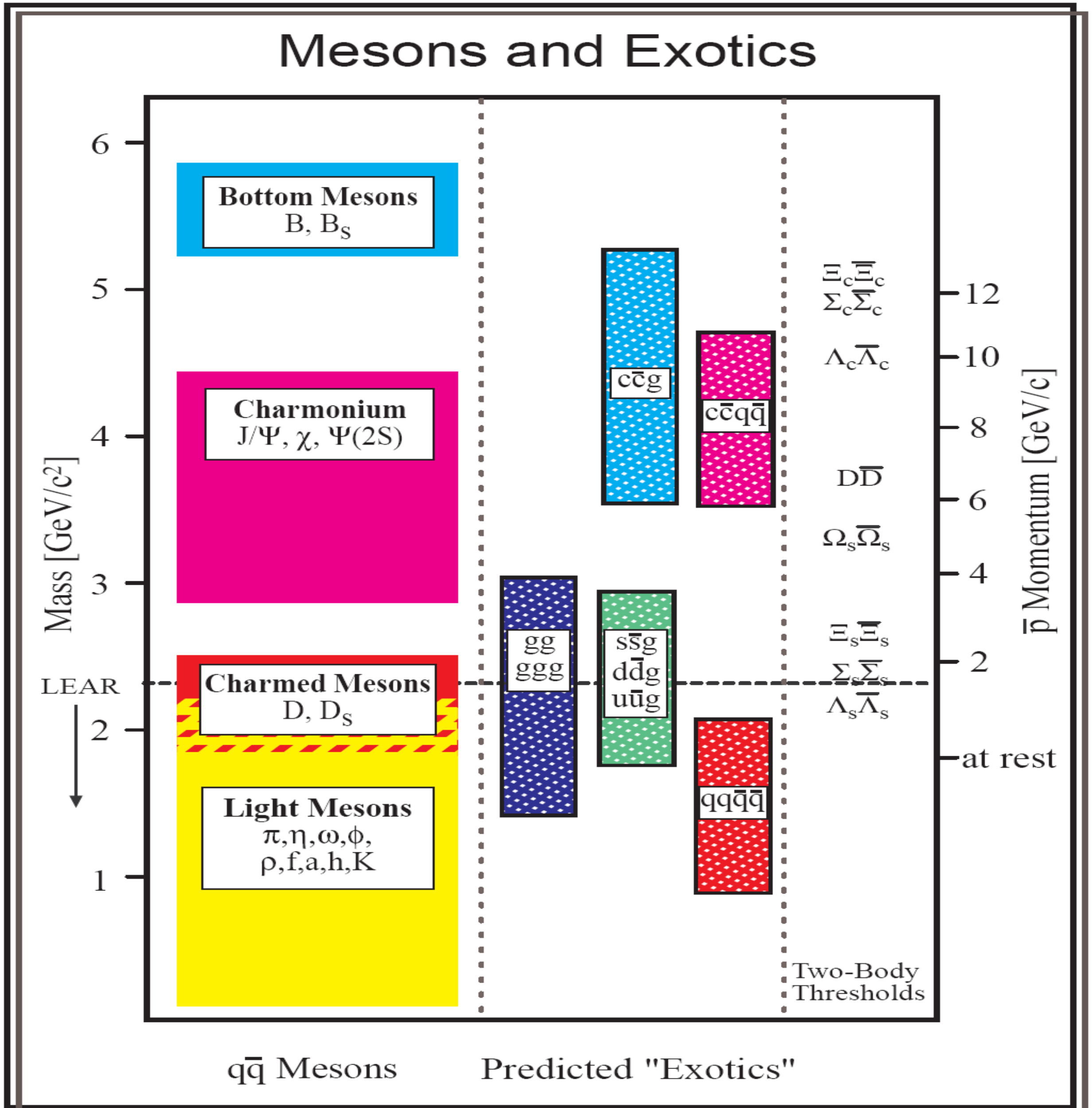
Proposed layout of HESR at FAIR

Complex NICA

Collider basic parameters:
$\sqrt{s_{NN}}$ = **4-11** GeV; ***beams***: *from* **p** to **Au**; **L**~**10^{27}** cm^{-2} c^{-1} (Au), ~**10^{32}** cm^{-2} c^{-1} (p)



WHY WE CONCENTRATE ON PHYSICS WITH ANTIPROTONS AND PROTONS



Expected masses of $\bar{q}\bar{q}$-mesons, glueballs, hybrids and two-body production thresholds.

Outline

- Physics case
- Conventional & exotic hadrons
- Review of recent experimental data
- Analysis & results
- Summary & perspectives

Why is charmonium-like (with a hidden charm) state chosen!? Charmonium-like state possesses some well favored characteristics:

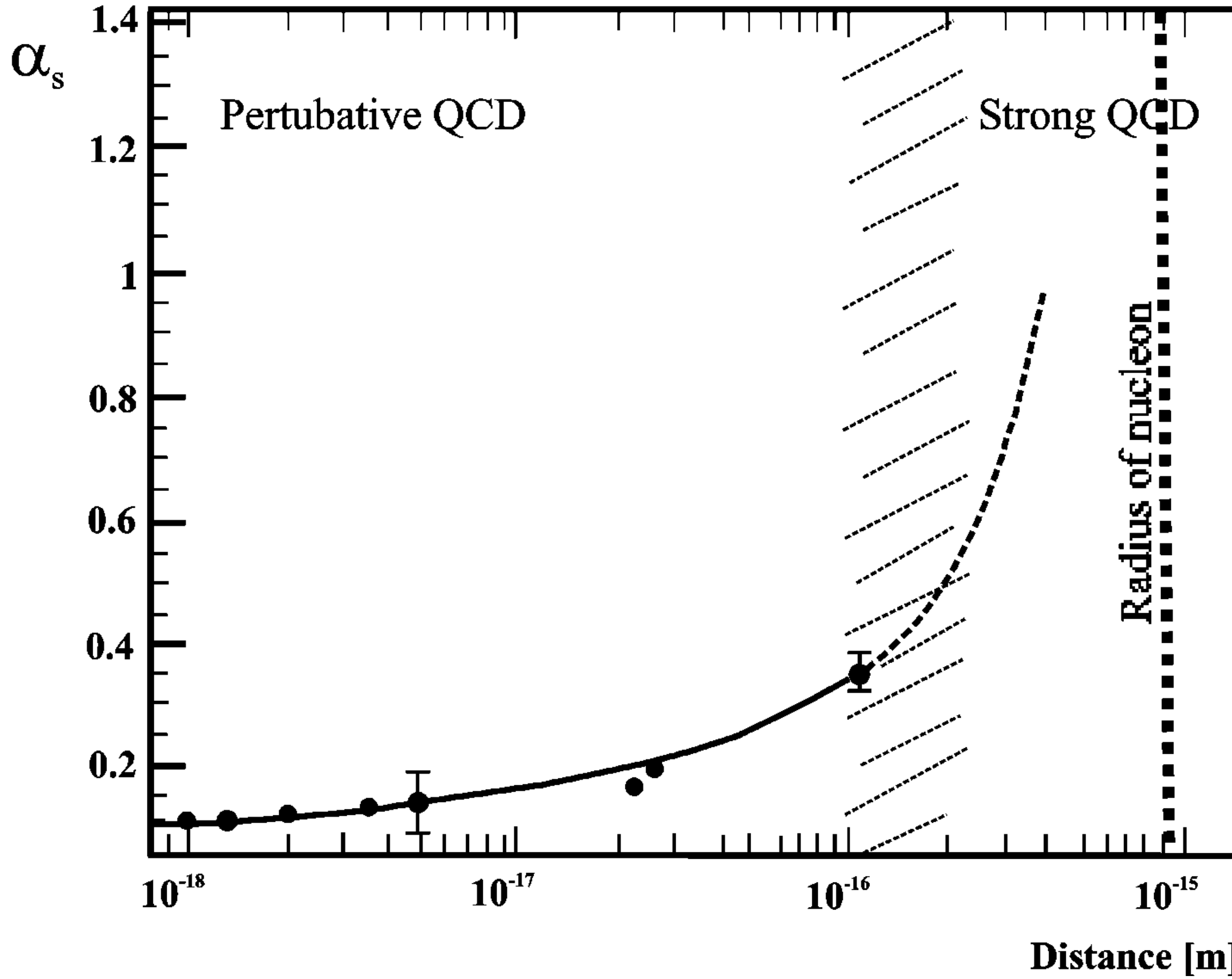
- is the simplest two-particle system consisting of quark & antiquark;
- is a compact bound system with small widths varying from several tens of keV to several tens of MeV compared to the light unflavored mesons and baryons
- charm quark *c* has a large mass (1.27 $\pm$ 0.07 GeV) compared to the masses of *u, d* & *s* (~ 0.1 GeV) quarks, that makes it plausible to attempt a description of the dynamical properties of charmonium-like system in terms of non-relativistic potential models and phenomenological models;
- quark motion velocities in charmonium-like systems are non-relativistic (the coupling constant, $\alpha_s \approx 0.3$ is not too large, and relativistic effects are manageable ($v^2/c^2 \approx 0.2$));
- the size of charmonium-like systems is of the order of less than 1 Fm $(R_{c\bar{c}} \sim \alpha_s \cdot m_q)$ so that one of the main doctrines of QCD – asymptotic freedom is emerging;

<u>Therefore</u>:

♦ charmonium-like studies are promising for understanding the dynamics of quark interaction at small distances;

♦ charmonium-like spectroscopy is a good testing ground for the theories of strong interactions:

  - QCD in both perturbative and nonperturbative regimes
  - QCD inspired potential models and phenomenological models



Coupling strength between two quarks as a function of their distance. For small distances ($\leq 10^{-16}$ m) the strengths α_s is ≈ 0.1, allowing a theoretical description by perturbative QCD. For distances comparable to the size of the nucleon, the strength becomes so large (strong QCD) that quarks can not be further separated: they remain confined within the nucleon and another theoretical approaches must be developed and applicable.

For charmonium (charmonium-like) states $\alpha_s \approx 0.3$ and $\langle v^2/c^2 \rangle \approx 0.2$.

The quark potential models have successfully described the charmonium spectrum, which generally assumes short-range coulomb interaction and long-range linear confining interaction plus spin dependent part coming from one gluon exchange. The zero-order potential is:

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}},$$

where $\tilde{\delta}_\sigma(r) = (\sigma/\sqrt{\pi})^3 e^{-\sigma^2 r^2}$ defines a gaussian-smeared hyperfine interaction.

Solution of equation with $H_0 = p^2/2m_c + V_0^{(c\bar{c})}(r)$ gives zero order charmonium wavefunctions.

*T. Barnes, S. Godfrey, E. Swangon, Phys. Rev. D 72, 054026 (2005), hep-ph/ 0505002 & Ding G.J. et al., arXiV: 0708.3712 [hep-ph], 2008

The splitting between the multiplets is determined by taking the matrix element of the $V_{spin\text{-}dep}$ taken from one-gluon exchange Breit-Fermi-Hamiltonian between zero-order wave functions:

$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}\mathrm{T}\right]$$

where α_s - coupling constant, *b* - string tension, σ - hyperfine interaction smear parameter.

Izmestev A. has shown * Nucl. Phys., V.52, N.6 (1990) & *Nucl. Phys., V.53, N.5 (1991) that in the case of curved coordinate space with radius *a* (confinement radius) and dimension *N* at the dominant time component of the gluonic potential the quark-antiquark potential defines via Gauss equations. If space of physical system is compact (sphere S^3), the harmonic potential assures confinement: * Advances in Applied Clifford Algebras, V.8, N.2, p.235 - 270 (1998) .

$$\Delta V_N(\vec{r}) = \text{const}\, G_N^{-1/2}(r)\delta(\vec{r}), \qquad V_N(r) = V_0\int D(r)R^{1-N}(r)dr/r,\ V_0 = \text{const} > 0.$$

$$R(r) = \sin(r/a),\ D(r) = r/a, \qquad V_3(r) = -V_0\,\text{ctg}(r/a) + B, \quad V_0 > 0, \quad B > 0.$$

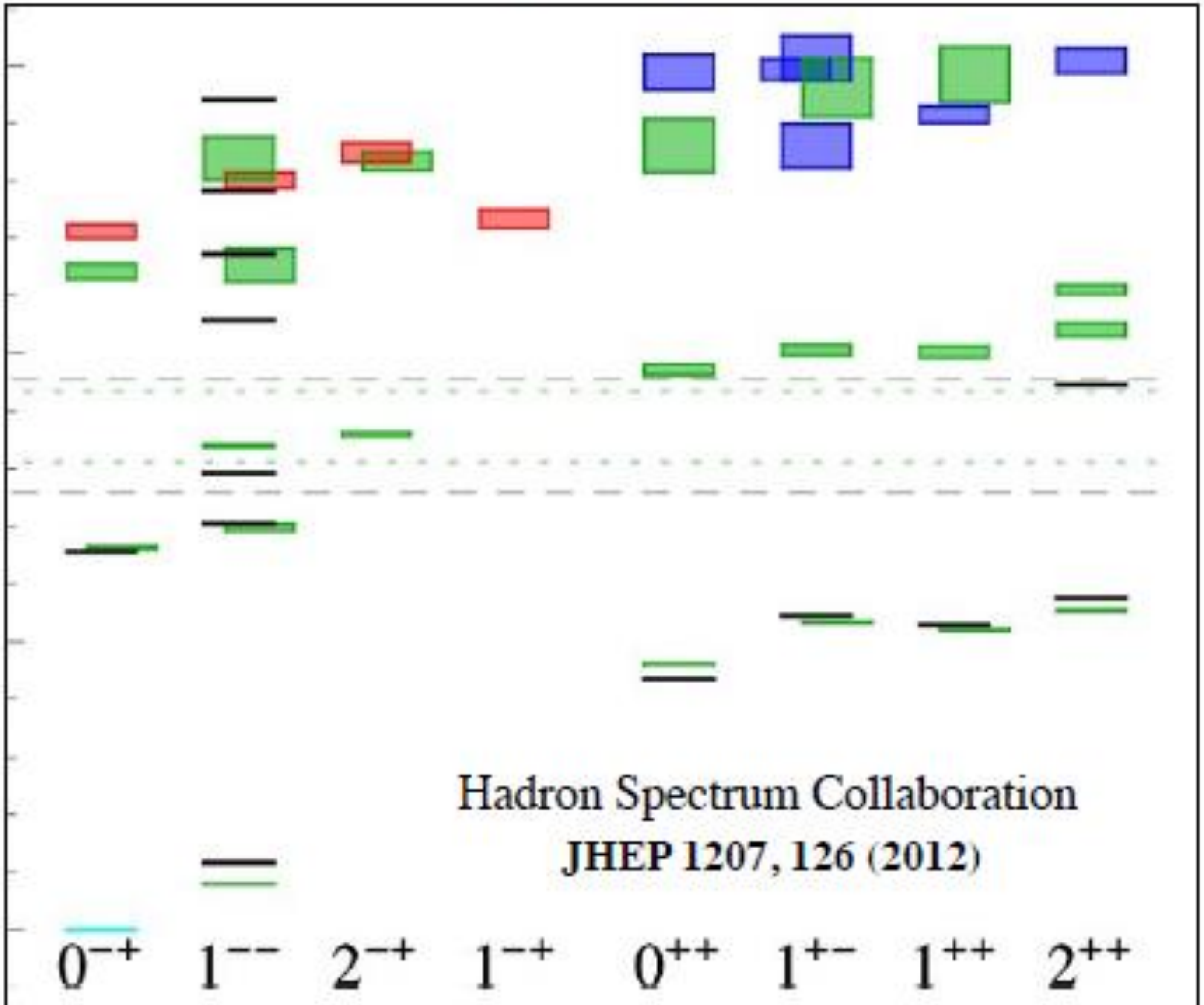
When cotangent argument in $V_3(r)$ is small: $r^2/a^2 << \pi^2$,

we get: $ctg(r/a) \approx a/r - r/3a$, $\Longrightarrow$ $\begin{cases} V(r)|_{r\to 0} \sim 1/r \\ V(r)|_{r\to\infty} \sim kr \end{cases}$

where *R(r), D(r)* and $G_N(r)$ are scaling factor, gauging and determinant of metric tensor $G_{\mu\nu}(r)$.

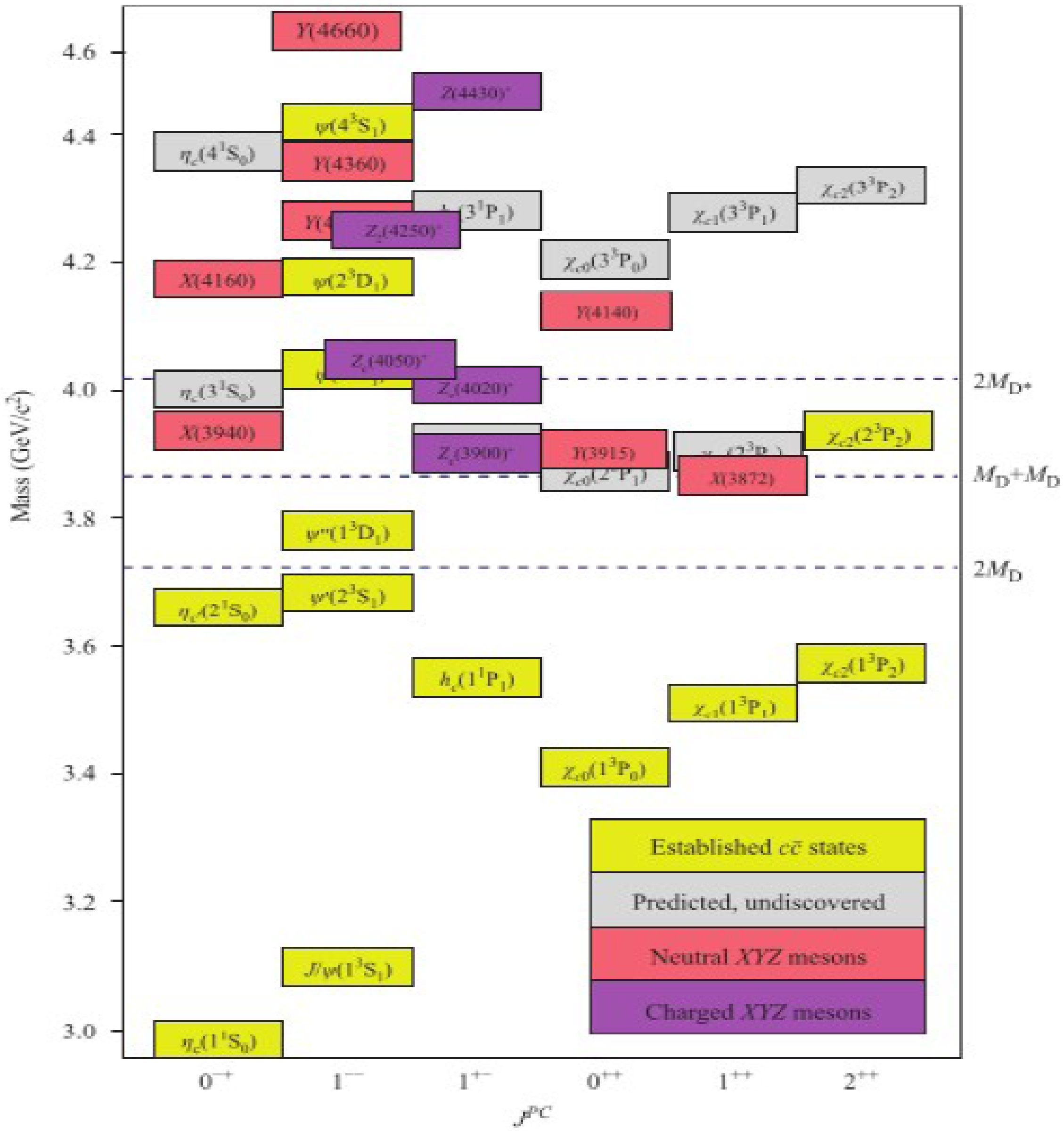
A more fundamental approach,

Lattice QCD:



CHARMONIUM-LIKE SPECTROSCOPY

played important role in establishing QCD as theory of strong interactions



S.L.Olsen
arXiv 1411.7738

- Below the open charm threshold the spectrum well understood
  - very good agreement between predicted and discovered states
- Above the threshold the situation in more complex
  - only few of the predicted states have been found
  - in the last decades many new states have been observed with properties that are not consistent with expectations for charmonium: X, Y, Z

X states:

- charmonium-like states with $J^{PC} \neq 1^{--}$
- Observed in B decays, pp and pp collisions

Y states:

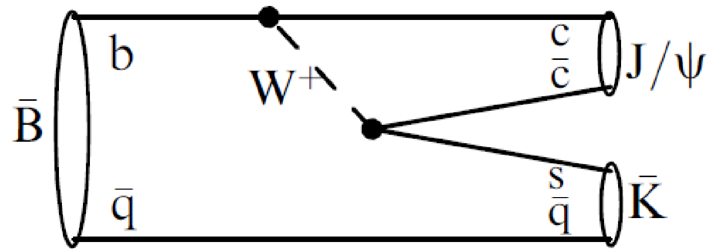
- charmonium-like states with $J^{PC} = 1^{--}$
- Observed in direct e + e - annihilation or in ISR

Z states:

- Must contain at least a cc and a light qq pair

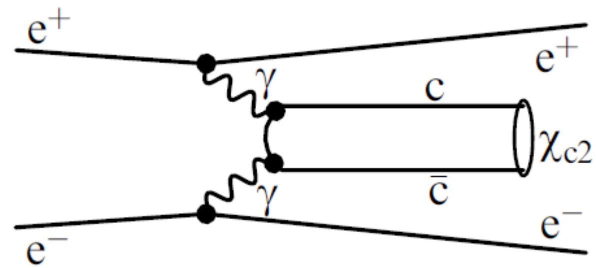
CHARMONIUM – LIKE PRODUCTION MECHANISMS RELEVANT TO THE *XYZ* – STATES

B-decays



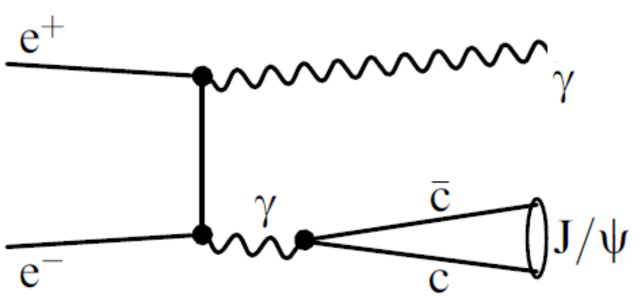
Any quantum numbers are possible, can be measure in angular analysis (Dalitz plot)

γγ fusion



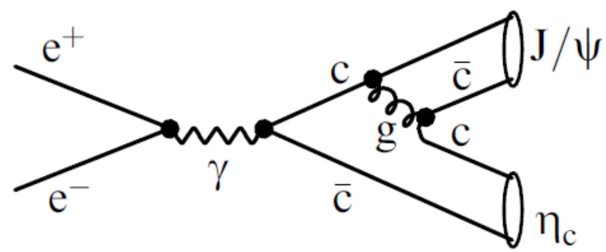
$J^{PC} = 0^{\pm +}, 2^{\pm +}$

annihilation with initial state radiation



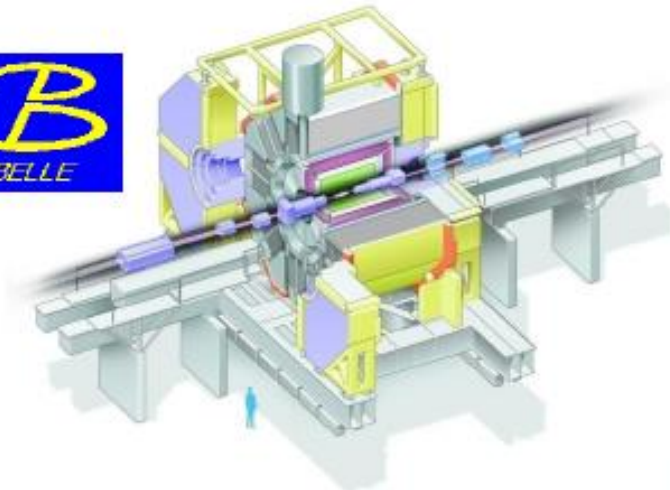
$J^{PC} = 1^{--}$

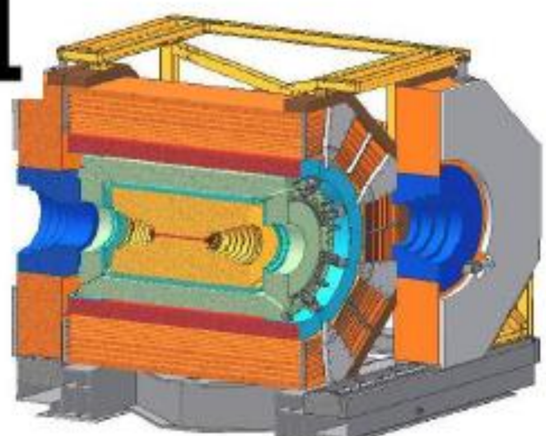
double charmonium production

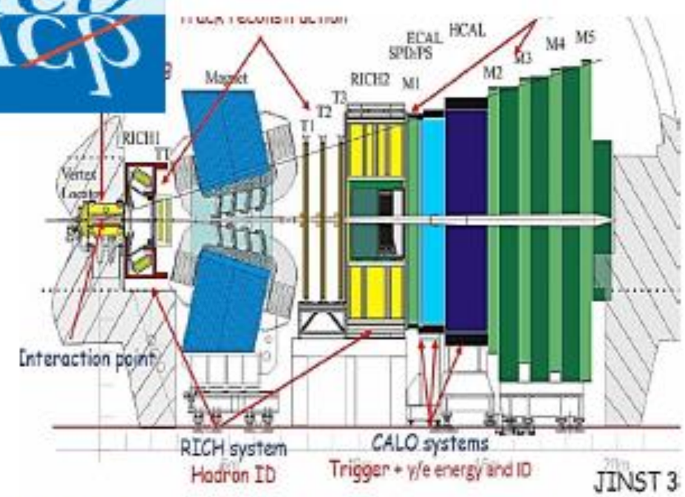


in association with J/ψ only $J^{PC} = 0^{\pm +}$ seen

Results from These Experiments

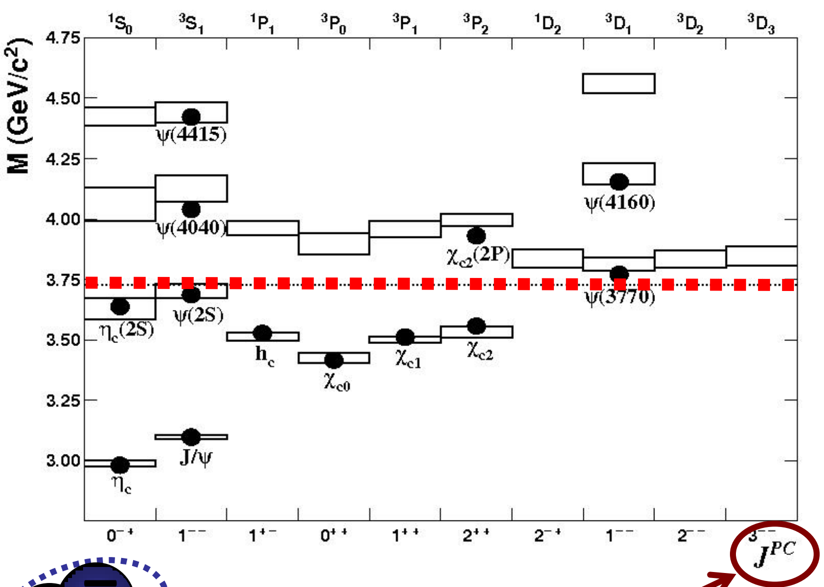


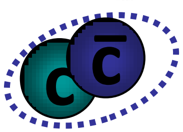




+ CLEOc, CDF, CMS/ATLAS …

Conventional charmonium





J = S + L

P = (–1)$^{L+1}$

C = (–1)$^{L+S}$

$n^{(2S+1)}L_J$

n radial quantum number

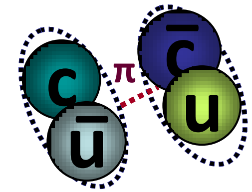
S total spin of QQbar

L relative orbital ang. mom.

Exotic charmonium-like states

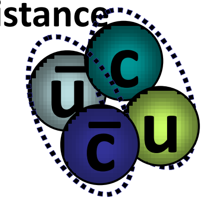
- **Multiquark states**
  - ***Molecular state***

    two loosely bound charm mesons
    - quark/color exchange at short distances
    - pion exchange at large distance

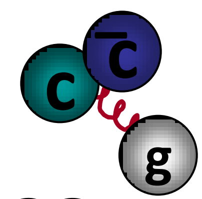


  - ***Tetraquark***

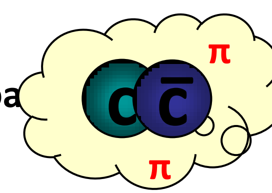
    tightly bound four-quark state



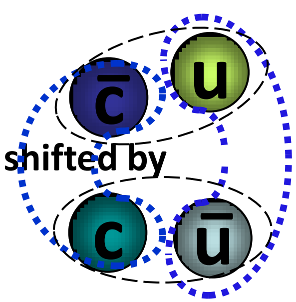
- **Charmonium hybrids**
  - States with excited gluonic degrees of freedom



- **Hadro-charmonium**
  - Specific charmonium state “coa light-hadron matter



- **Threshold effects**
  - Virtual states at thresholds
  - Charmonium states with masses shifted by nearby $D_{(s)}^{(*)}D_{(s)}^{(*)}$ thresholds



- Rescattering
  - Two D-mesons, produced closely

Two different kinds of experiments are foreseen:

- production experiment – $\bar{p}p \to X + M$, where $M = \pi, \eta, \omega, \ldots$ (conventional states plus states with exotic quantum numbers)
- formation experiment (annihilation process) – $\bar{p}p \to X \to M_1M_2$ (conventional states plus states with non-exotic quantum numbers)

The low laying charmonium hybrid states:

	Gluon	
$(q\bar{q})_8$	1^- (TM)	1^+ (TE)
${}^1S_0$, 0^{-+}	1^{++}	1^{--}
${}^3S_1$, 1^{--}	0^{+-} ← exotic	0^{-+}
	1^{+-}	1^{-+} ← exotic
	2^{+-} ← exotic	2^{-+}

Charmonium-like exotics (hybrids, tetraquarks) predominantly decay via electromagnetic and hadronic transitions and into the open charm final states:

- $c\bar{c}g \to (\Psi, \chi_{cJ})$ + light mesons $(\eta, \eta', \omega, \varphi)$ and $(\Psi, \chi_{cJ}) + \gamma$ - these modes supply small widths and significant branch fractions;
- $c\bar{c}g \to D\bar{D}_J^*$. In this case *S-wave (L = 0)* + *P-wave (L = 1)* final states should dominate over decays to $D\bar{D}$ (are forbidden → *CP* violation) and partial width to should be very small.

The most interesting and promising decay channels of charmed hybrids have been, in particular, analyzed:

- $\bar{p}p \to \tilde{\eta}_{c0,1,2}\ (0^{-+}, 1^{-+}, 2^{-+})\ \eta \to \chi_{c0,1,2}\ (\eta, \pi\pi, \gamma; \ldots)$;
- $\bar{p}p \to \tilde{h}_{c0,1,2}\ (0^{+-}, 1^{+-}, 2^{+-})\ \eta \to \chi_{c0,1,2}\ (\eta, \pi\pi, \gamma; \ldots)$;
- $\bar{p}p \to \tilde{\Psi}\ (0^{--}, 1^{--}, 2^{--}) \to J/\Psi\ (\eta, \omega, \pi\pi, \gamma \ldots)$;
- $\bar{p}p \to \tilde{\eta}_{c0,1,2},\ \tilde{h}_{c0,1,2},\ \tilde{\chi}_{c1}\ (0^{-+}, 1^{-+}, 2^{-+}, 0^{+-}, 1^{+-}, 2^{+-}, 1^{++})\ \eta \to D\bar{D}_J^*\ (\eta, \gamma)$.

$J^{PC} = 0^{--} \to$ exotic!

According the constituent quark model tetraquark states are classified in terms of the diquark and diantiquark spin S_{cq}, $S_{\overline{cq}'}$, total spin of diquark-diantiquark system S, total angular momentum J, spacial parity P and charge conjugation C. The following states with definite quantum numbers J^{PC} are expected to exist:

- two states with $J = 0$ and positive P-parity $J^{PC} = 0^{++}$ *i.e.*, $|\, 0_{cq}, 0_{\overline{cq}'} \,;\, S = 0, J = 0 \,\rangle$ and $|\, 1_{cq}, 1_{\overline{cq}'} \,;\, S = 0, J = 0 \,\rangle$;
- three states with $J = 0$ and negative P-parity *i.e.*, $|A\,\rangle = |\, 1_{cq}, 0_{\overline{cq}'} \,;\, S = 1, J = 0 \,\rangle$; $|B\,\rangle = |\, 0_{cq}, 1_{\overline{cq}'} \,;\, S = 1, J = 0 \,\rangle$; $|C\,\rangle = |\, 1_{cq}, 1_{\overline{cq}'} \,;\, S = 1, J = 0 \,\rangle$. State $|C\,\rangle$ is even under charge conjugation. Taking symmetric and antisymmetric combinations of states $|A\,\rangle$ and $|B\,\rangle$ we obtain a C-odd and C-even state respectively; therefore we have one state with $J^{PC} = 0^{--}$ *i.e.*, $|\, 0^{--} \,\rangle = \frac{1}{\sqrt{2}}\left(|A\,\rangle + |B\,\rangle\right)$ and two states with $J^{PC} = 0^{-+}$ *i.e.*, $|\, 0^{-+} \,\rangle_1 = \frac{1}{\sqrt{2}}\left(|A\,\rangle - |B\,\rangle\right)$; $|\, 0^{-+} \,\rangle_2 = |\, C \,\rangle$.
- three states with $J = 1$ and positive P-parity *i.e.*, $|D\rangle = |\, 1_{cq}, 0_{\overline{cq}'} \,;\, S = 1, J = 1 \,\rangle$; $|E\rangle = |\, 0_{cq}, 1_{\overline{cq}'} \,;\, S = 1, J = 1 \,\rangle$; $|F\rangle = |\, 1_{cq}, 1_{\overline{cq}'} \,;\, S = 1, J = 1 \,\rangle$. State $|F\,\rangle$ is odd under charge conjugation. Operating $|D\rangle$ and $|E\rangle$ in the same way as for states $|A\,\rangle$ and $|B\,\rangle$ we obtain one state with $J^{PC} = 1^{++}$ state *i.e.*, $|\, 1^{++} \,\rangle = \frac{1}{\sqrt{2}}\left(|D\,\rangle + |E\,\rangle\right)$ and two states with $J^{PC} = 1^{+-}$ *i.e.*, $|\, 1^{+-} \,\rangle_1 = \frac{1}{\sqrt{2}}\left(|D\,\rangle - |E\,\rangle\right)$; $|\, 1^{+-} \,\rangle_2 = |F\rangle$.
- one state with $J = 2$ and positive P-parity $J^{PC} = 2^{++}$ *i.e.*, $|\, 1_{cq}, 1_{\overline{cq}'} \,;\, S = 1, J = 2 \,\rangle$.

!

- $\bar{p}p \to X \to J/\Psi\,\rho \to J/\Psi\,\pi\pi$; $\bar{p}p \to X \to J/\Psi\,\omega \to J/\Psi\,\pi\pi\pi$, $\bar{p}p \to X \to \chi_{cJ}\,\pi$ (decays into J/Ψ, Ψ', χ_{cJ} and light mesons);
- $\bar{p}p \to X \to D\overline{D}^* \to D\overline{D}\,\gamma$; $\bar{p}p \to X \to D\overline{D}^* \to D\overline{D}\,\eta$ (decays into $D\overline{D}^*$-pair).

Z_c States

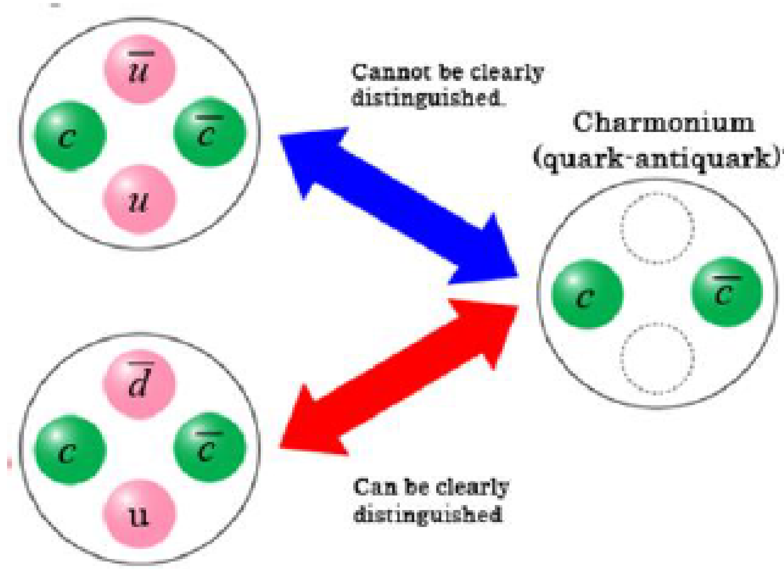
$cu\bar{c}\bar{d}$ $cd\bar{c}\bar{s}$ $cu\bar{c}\bar{s}$

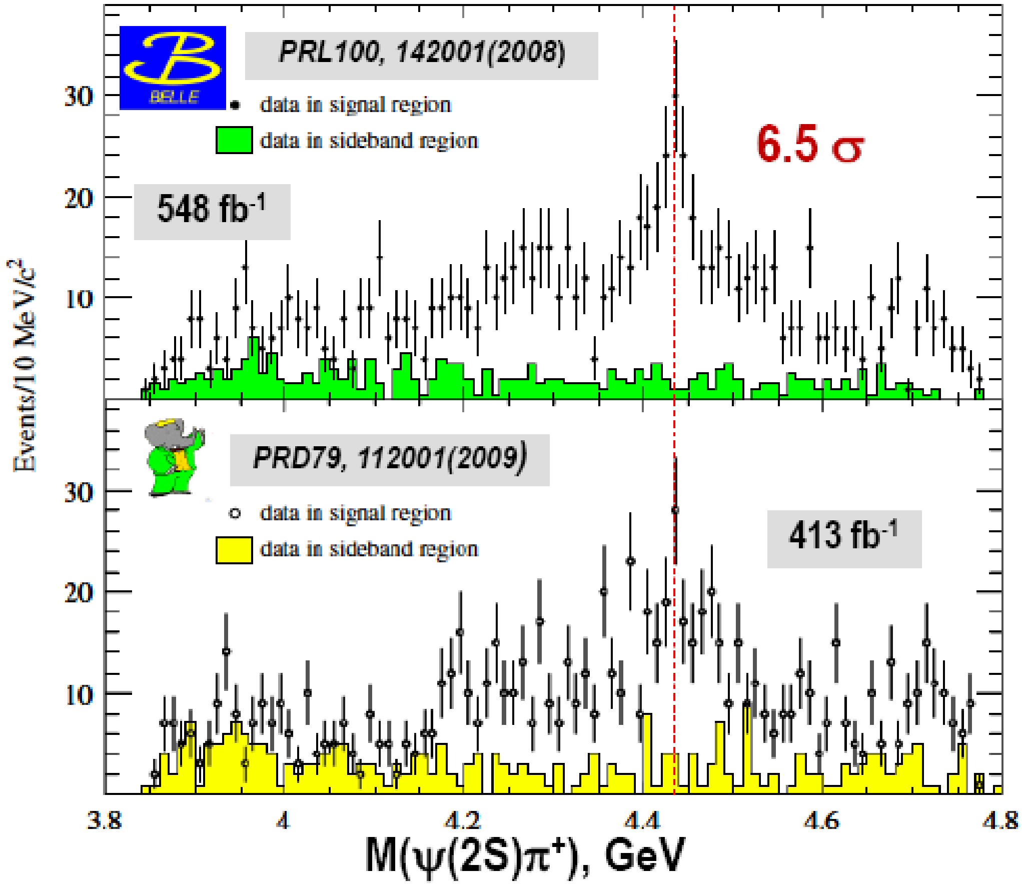
The most promising way to searching for the exotic hadrons

- Decay into a charmonium or $D^{(*)}\bar{D}^{(*)}$ pair
  - thus contains hidden-$c\bar{c}$ pair
- Have electric charge,
  - thus has two more light quarks

At least 4 quarks, not a conventional meson

- Observed in final states :
  - $\pi^{\pm}J/\psi$, $\pi^{\pm}\psi(2S)$, $\pi^{\pm}h_c$, $\pi^{\pm}\chi_{cJ}$, $(D^{(*)}\bar{D}^{(*)})^{\pm}$,...
- Experimental search:
  - BESIII/CLEO-c : $e^+e^- \to \pi^{\pm}$ +Exotics, ...
  - Belle/BaBar : $e^+e^- \to (\gamma_{ISR})\pi^{\pm}$+Exotics, ...
  - Belle/BaBar/LHCb: $B \to K^{\pm}$+Exotics, ...





$Z(4430)^+$

The first measurement

Fit to $M(\psi(2S)\pi^+)$

$K^*(890)$ and $K^*(1430)$ veto

$M = (4433 \pm 4 \pm 2)$ MeV/c^2

$\Gamma = (45^{+18}_{-13}{}^{+30}_{-13})$ MeV

PRD 80, 031104 (2009)

Confirmation

Dalitz analysis

$M = (4443^{+15}_{-12}{}^{+17}_{-13})$ MeV/c^2

$\Gamma = (109^{+86}_{-43}{}^{+57}_{-52})$ MeV

PRD 88,074026(2013)

Full amplitude analysis to obtain spin-parity $J^P = 1^+$

$M = (4485 \pm 22{}^{+28}_{-11})$ MeV/c^2

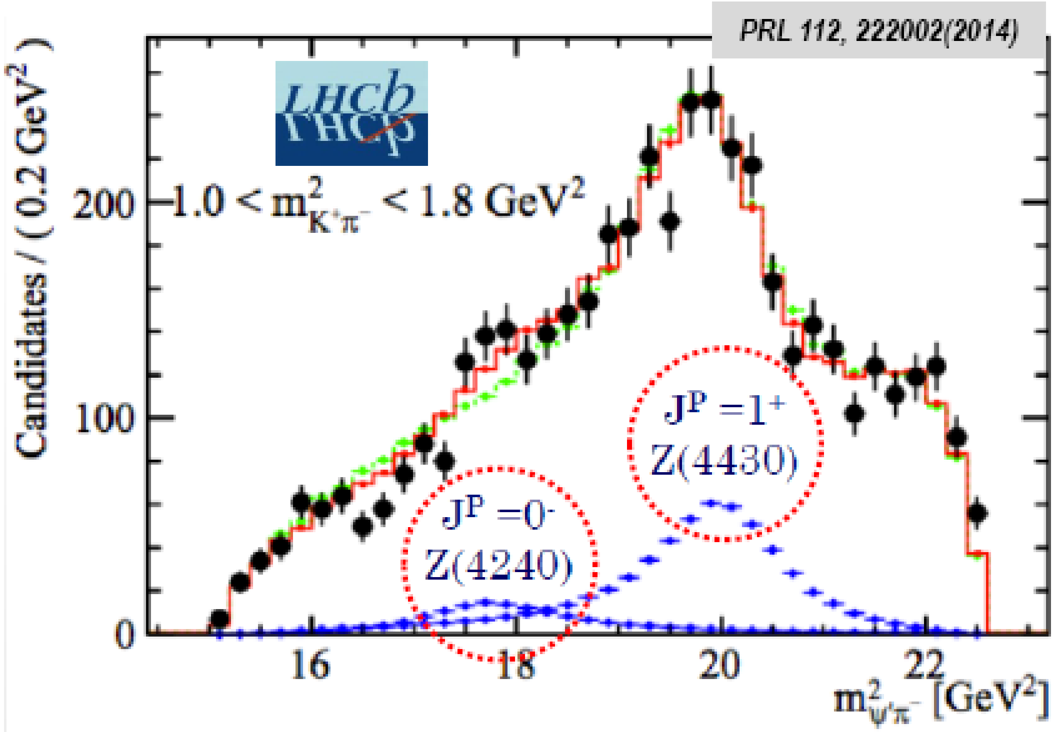
$\Gamma = (200^{+41}_{-46}{}^{+26}_{-35})$ MeV

$Br(B \to KZ^+) \times Br(Z^+ \to \psi(2S)\pi^+) =$

The first measurement	$(4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$
Dalitz analysis	$(3.2^{+1.8}_{-0.9}{}^{+5.3}_{-1.6}) \times 10^{-5}$
	$< 3.1 \times 10^{-5}$ at 95% CL

BaBar does not confirm Belle,
but also does not rule it out!
Task for Belle II and LHCb

Z(4430)$^+$ at LHCb



$$M_{Z_0} = 4239 \pm 18^{+45}_{-10}\,\text{MeV}$$
$$\Gamma_{Z_0} = 220 \pm 47^{+108}_{-74}\,\text{MeV}$$
$$f_{Z_0} = (1.6 \pm 0.5^{+1.9}_{-0.4})\%$$

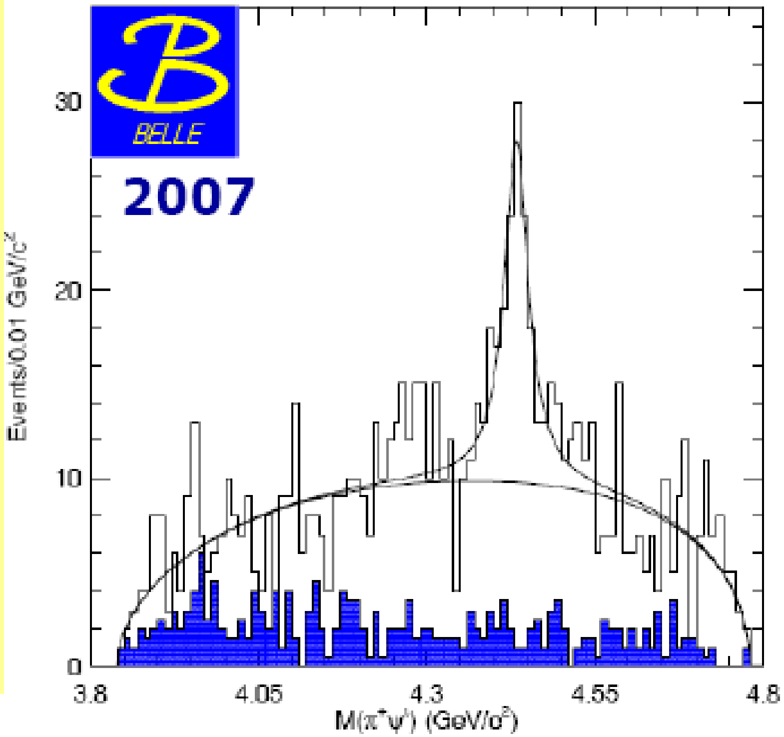
- Significance is >14 σ
- Phase motion consistent with resonance (Breit-Wigner)
- Parameters (including quantum numbers) are consistent with the Belle results
- Another peak at 4200 MeV with significance ~5 σ

Charged Charmonium-like States

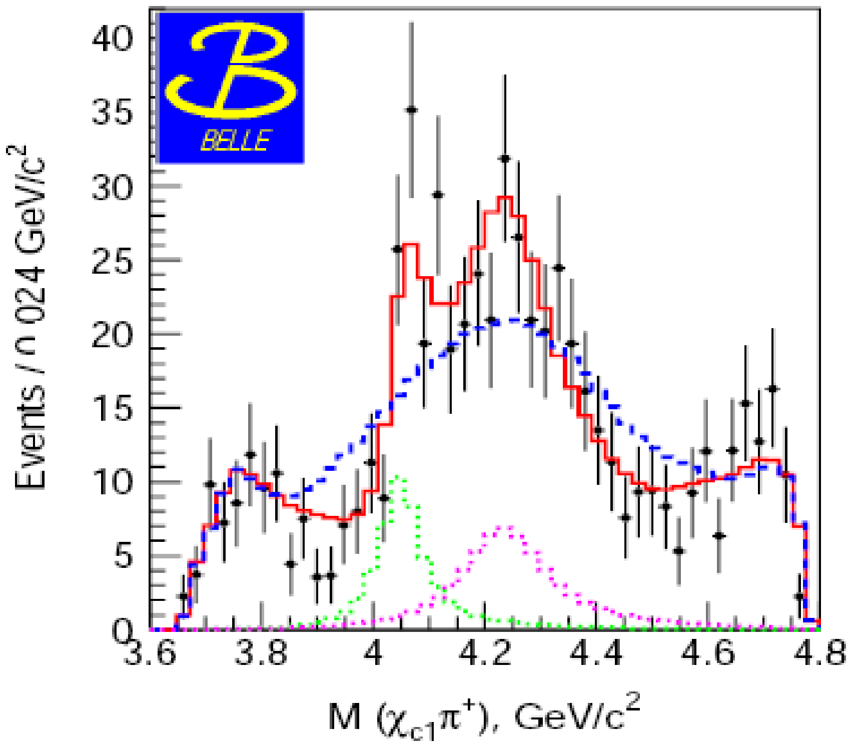
$Z(4430)^+$, $Z(4050)^+$, $Z(4250)^+$ at Belle

PRL 100, 142001 (2008)

$B^0 \to \pi^+ \psi(2S) K^-$



$B^0 \to \pi^+ \chi_{c1} K^-$



PRD 78, 072004 (2008)

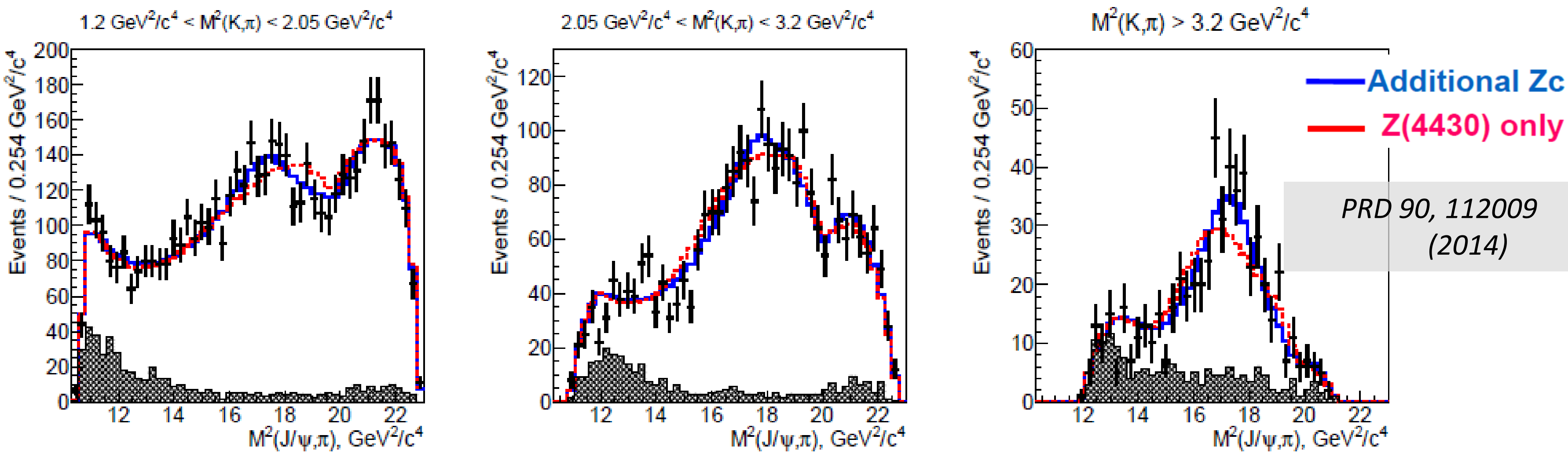
Total significance: 6.5 σ and >5σ for each Z^+

Because they are charged, these states cannot be pure cc-bar

Z(4200) at Belle

4D-fit: Dalitz+angular variables

$B \to K^- \pi^+ J/\psi(\to \ell^+ \ell^- \psi)$



PRD 90, 112009 (2014)

Model: sum of all K(*(*)) + Z

- New Z_c^+ is found ($J^P=1^+$), 6.2 σ with systematics
- $M = 4196^{+31}_{-29}{}^{+17}_{-13}$ MeV; $\Gamma = 370^{+70}_{-70}{}^{+70}_{-132}$ MeV
- **Exclusion levels (other** $J^P=0^-, 1^-, 2^-, 2^+$): 6.1σ, 7.4σ, 4.4σ, 7.0σ.
- $Z_c^+(4430)$ is significant (though via negative interference): 4.0 σ evidence for new decay modes → J/ψ π
- **No signal of** $Z_c^+(3900)$

$$\frac{\Gamma(Z(4430)^+ \to J/\psi\,\pi)}{\Gamma(Z(4430)^+ \to \psi(2S)\,\pi)} = 0.09^{+0.08}_{-0.05}$$

suppressed despite larger phase space

SUMMARY on Zc from BES III

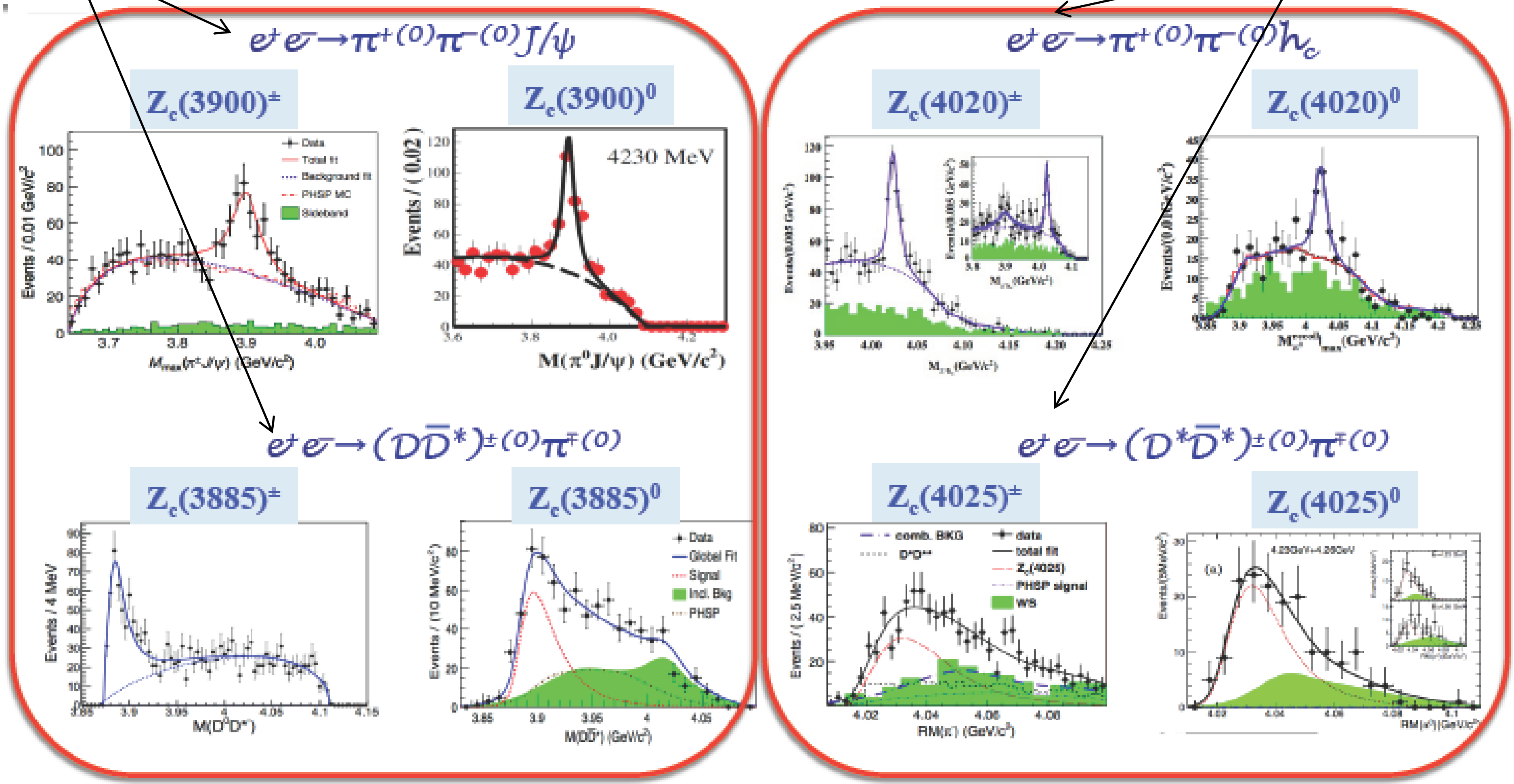
State]	Mass (MeV/c²)	Width (MeV)	Decay	Process	[Ref]
$Z_c(3900)^{\pm}$	3899.0±3.6±4.9	46±10±20	$\pi^{\pm}J/\psi$	$e^+e^- \to \pi^+\pi^-J/\psi$	[1]
$Z_c(3900)^0$	3894.8±2.3±2.7	29.6±8.2±8.2	π^0J/ψ	$e^+e^- \to \pi^0\pi^0J/\psi$	[2]
$Z_c(3885)^{\pm}$	3883.9±1.5±4.2 Single D tag	24.8±3.3±11.0 Single D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$	[3]
	3881.7±1.6±2.1 Double D tag	26.6±2.0±2.3 Double D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$	[4]
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7}\pm8.4$	$35^{+11}_{-12}\pm15$	$(D\bar{D}^*)^0$	$e^+e^- \to (D\bar{D}^*)^0\pi^0$	[5]
$Z_c(4020)^{\pm}$	4022.9±0.8±2.7	7.9±2.7±2.6	$\pi^{\pm}h_c$	$e^+e^- \to \pi^+\pi^-h_c$	[6]
$Z_c(4020)^0$	4023.9±2.2±3.8	fixed	π^0h_c	$e^+e^- \to \pi^0\pi^0h_c$	[7]
$Z_c(4025)^{\pm}$	4026.3±2.6±3.7	24.8±5.6±7.7	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$	[8]
$Z_c(4025)^0$	$4025.5^{+2,0}_{-4.7}\pm3.1$	23.0±6.0±1.0	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^0\pi^0$	[9]

[1] PRL,110,252001; [2] PRL 115, 112003; [3] PRL,112, 022001; [4] PRD 92, 092006
[5] PRL 115, 222002; [6] PRL,110, 252001; [7] PRL,113,212002; [9] PRL,112, 132001
[9] arXiv:1507.02404

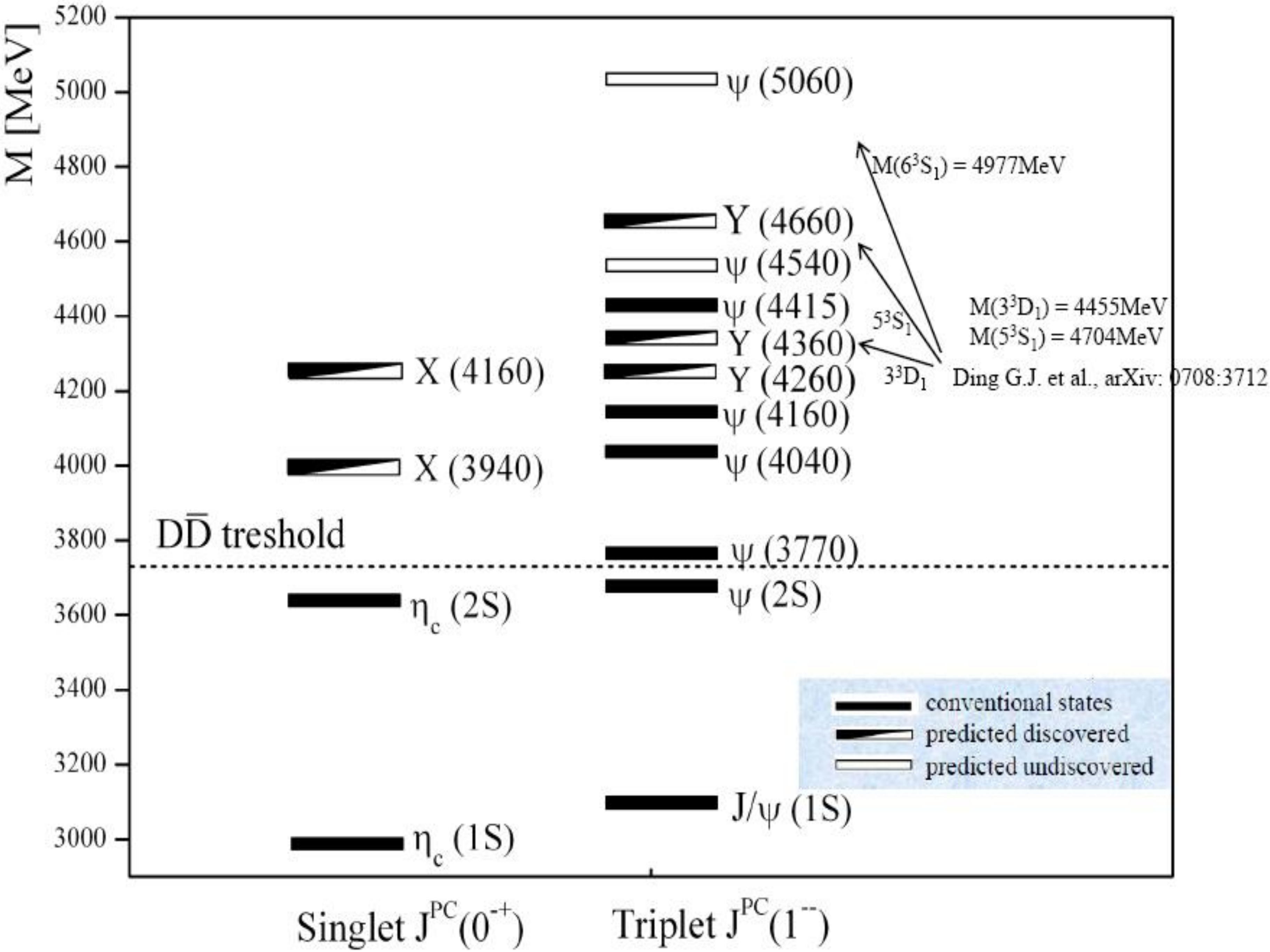
Are these states the same?!

SUMMARY on Zc from BES III

Are these states the same?!

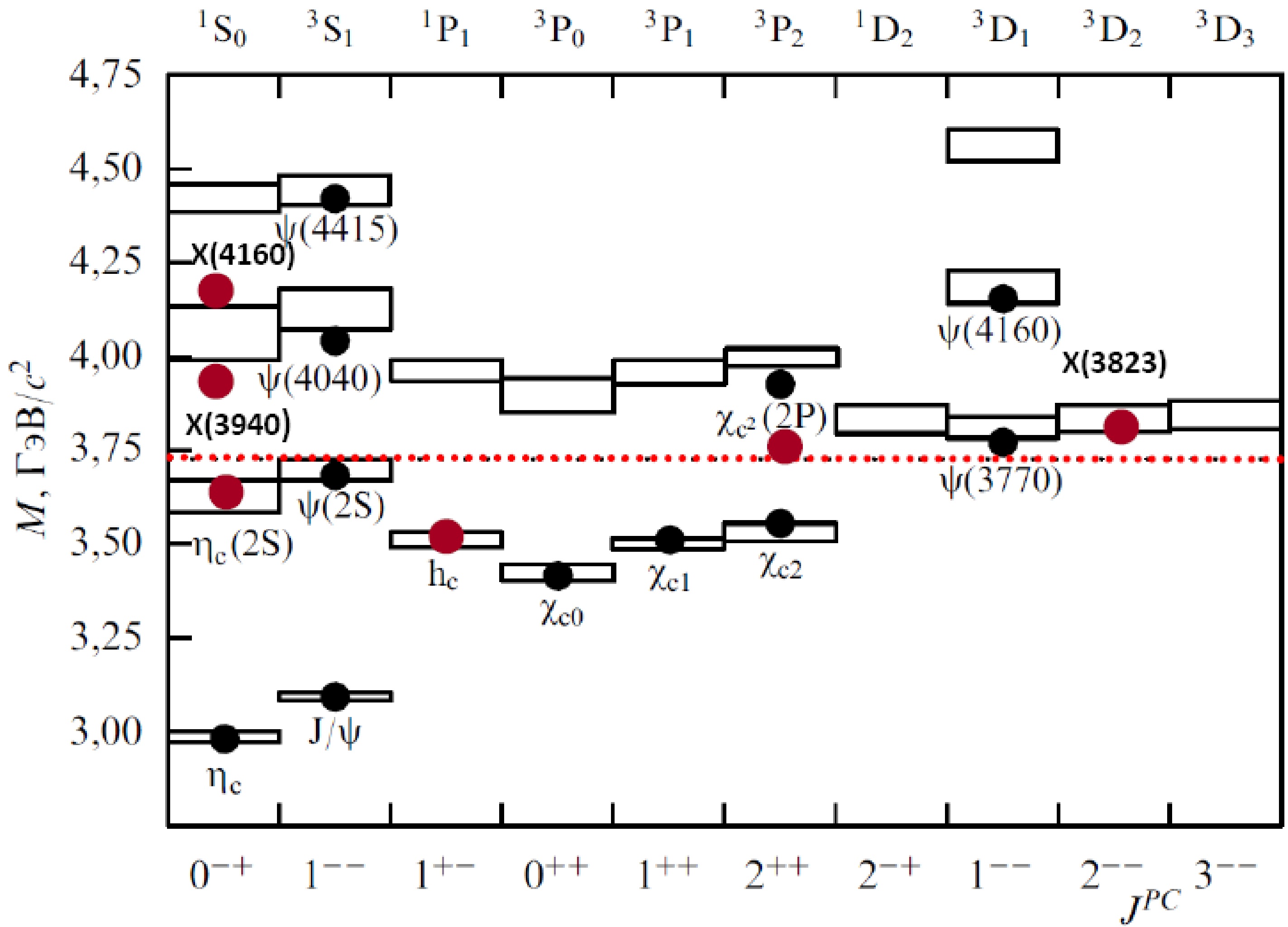


- Nature of these states? Isospin triplets?
- Different decay channels of the same states observed?
- Other decay modes?



M [MeV]
5200
5000
4800
4600
4400
4200
4000
3800
3600
3400
3200
3000
ψ (5060)
M(6³S₁) = 4977MeV
Y (4660)
ψ (4540)
ψ (4415)
5³S₁
M(3³D₁) = 4455MeV
M(5³S₁) = 4704MeV
Y (4360)
X (4160)
Y (4260)
3³D₁
Ding G.J. et al., arXiv: 0708:3712
ψ (4160)
X (3940)
ψ (4040)
DD̄ treshold
ψ (3770)
ψ (2S)
η_c (2S)
conventional states
predicted discovered
predicted undiscovered
J/ψ (1S)
η_c (1S)
Singlet J^PC(0^-+)
Triplet J^PC(1^--)

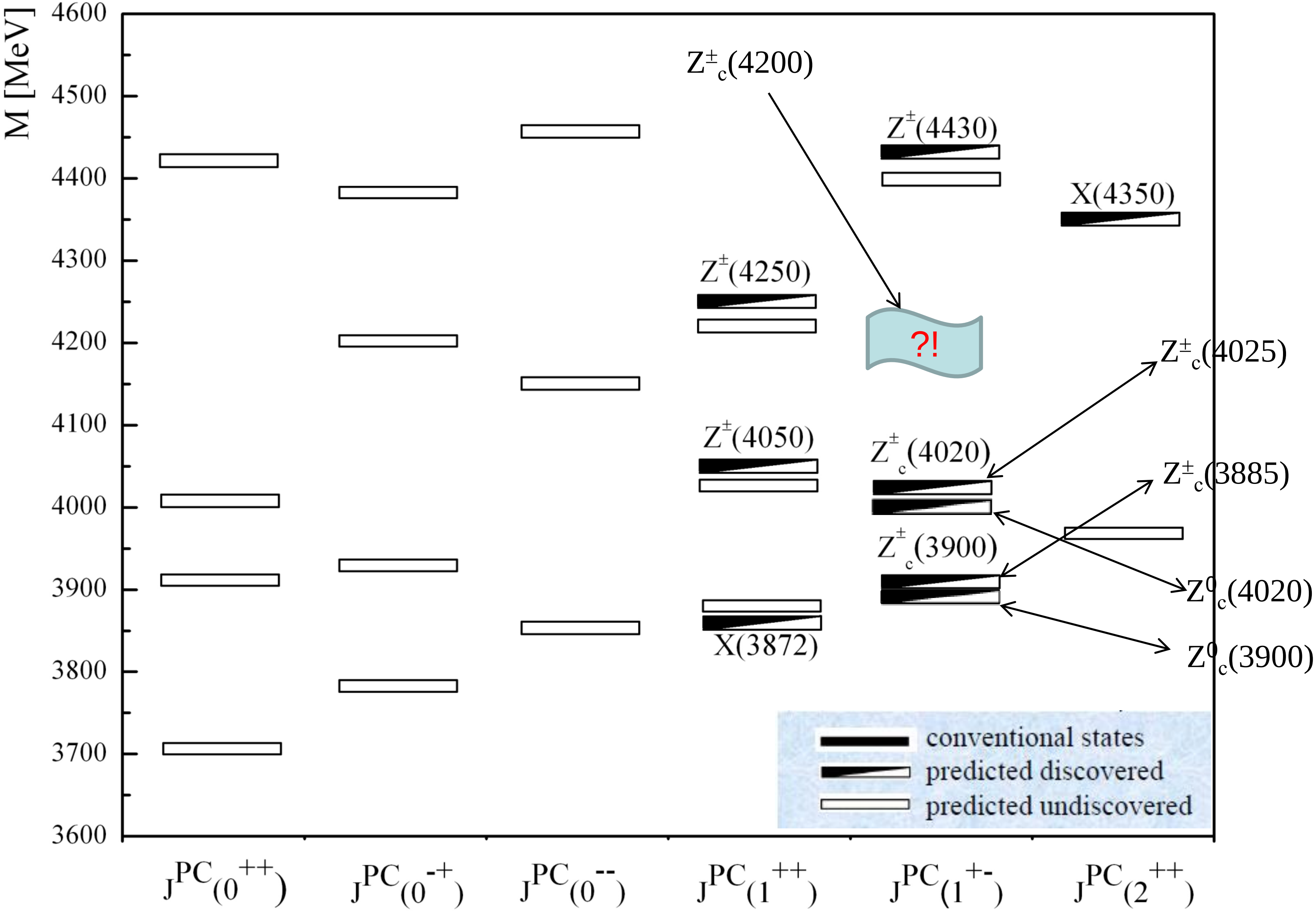
6 observed states can fit* into charmonium table



* However, not easily: potential models need to be elaborated to describe new masses

What about others?

THE SPECTRUM OF TETRAQUARKS WITH THE HIDDEN CHARM



M.Yu. Barabanov, S. L. Olsen, A.S. Vodopyanov, A.I. Zinchenko, Yad. Fiz., V.79, N.1, pp. 1-4 (2016) / Phys. At. Nucl., V.79, N.1, pp. 126 – 179 (2016)

What to look for

- Does the Z(4433) exist??
- Better to find charged X !
- Neutral partners of Z(4433)~X(1^{+-},2S) should be close by few MeV and decaying to $\psi(2S)\ \pi/\eta$ or $\eta_c(2S)\ \rho/\omega$
- What about X(1^{+-},1S)? Look for any charged state at ≈ 3880 MeV (decaying to $\psi\pi$ or $\eta_c\rho$)
- Similarly one expects X(1^{++},2S) states. Look at M~4200-4300: X(1^{++},2S)->$D^{(*)}D^{(*)}$
- Baryon-anti-baryon thresholds at hand (4572 MeV for $2M_{\Lambda c}$ and 4379 MeV for $M_{\Lambda c}+M_{\Sigma c}$). X($2^{++}$,2S) might be over bb-threshold.

(L.Maiani, A.D.Polosa, V.Riquer, 0708.3997

CALCULATION OF WIDTHS

The integral formalism (or in other words integral approach) is based on the possibility of appearance of the discrete quasi stationary states with finite width and positive values of energy in the barrier-type potential. This barrier is formed by the superposition of two type of potentials: short-range attractive potential $V_1(r)$ and long-distance repulsive potential $V_2(r)$.

Thus, the width of a quasi stationary state in the integral approach is defined by the following expression (integral formula):

$$\Gamma = 2\pi \left| \int_0^\infty \phi_L(r) V(r) F_L(r) r^2 dr \right|^2$$

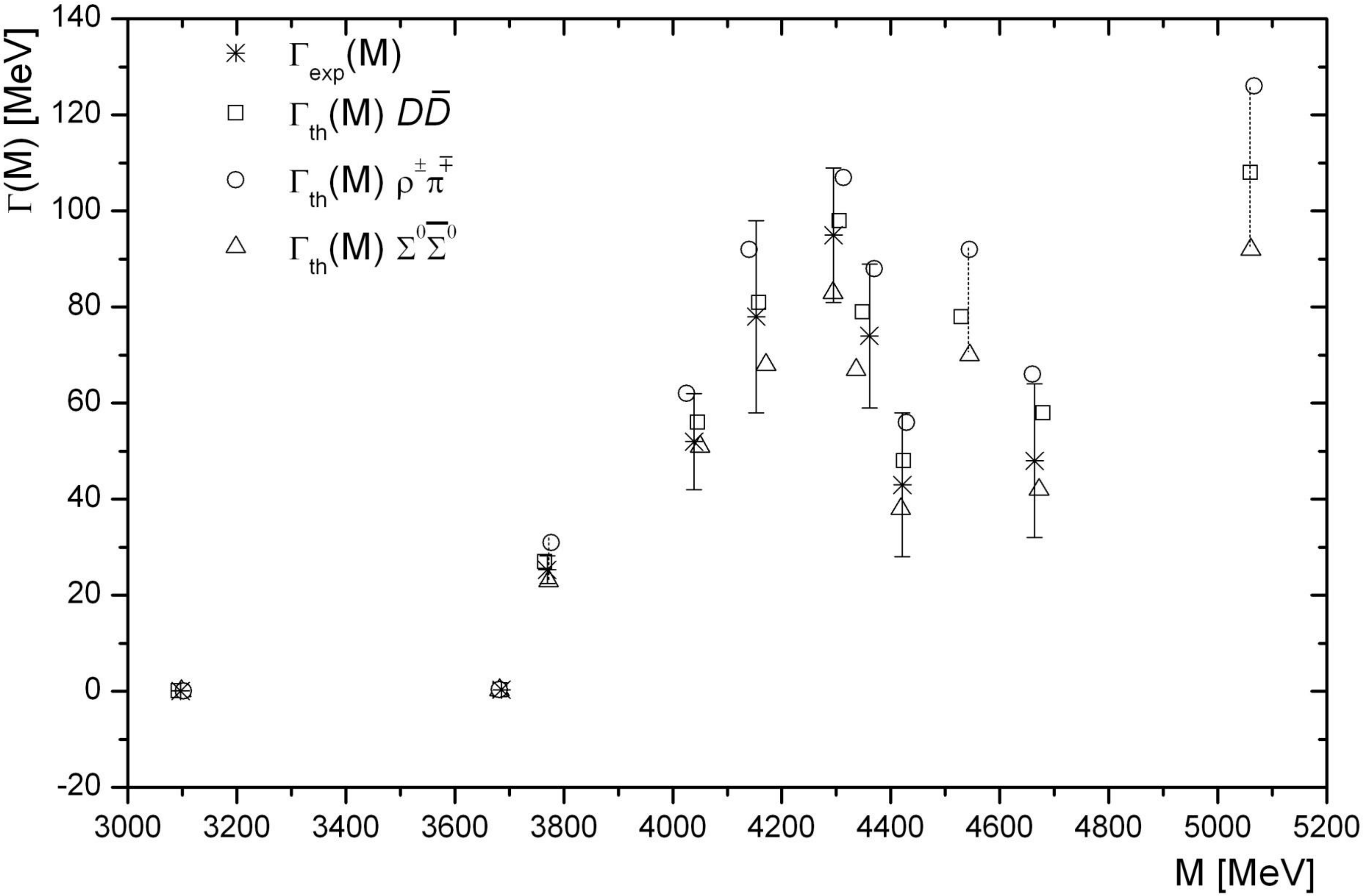
$$(r < R): \int_0^R |\phi_L(r)|^2 \, dr = 1$$

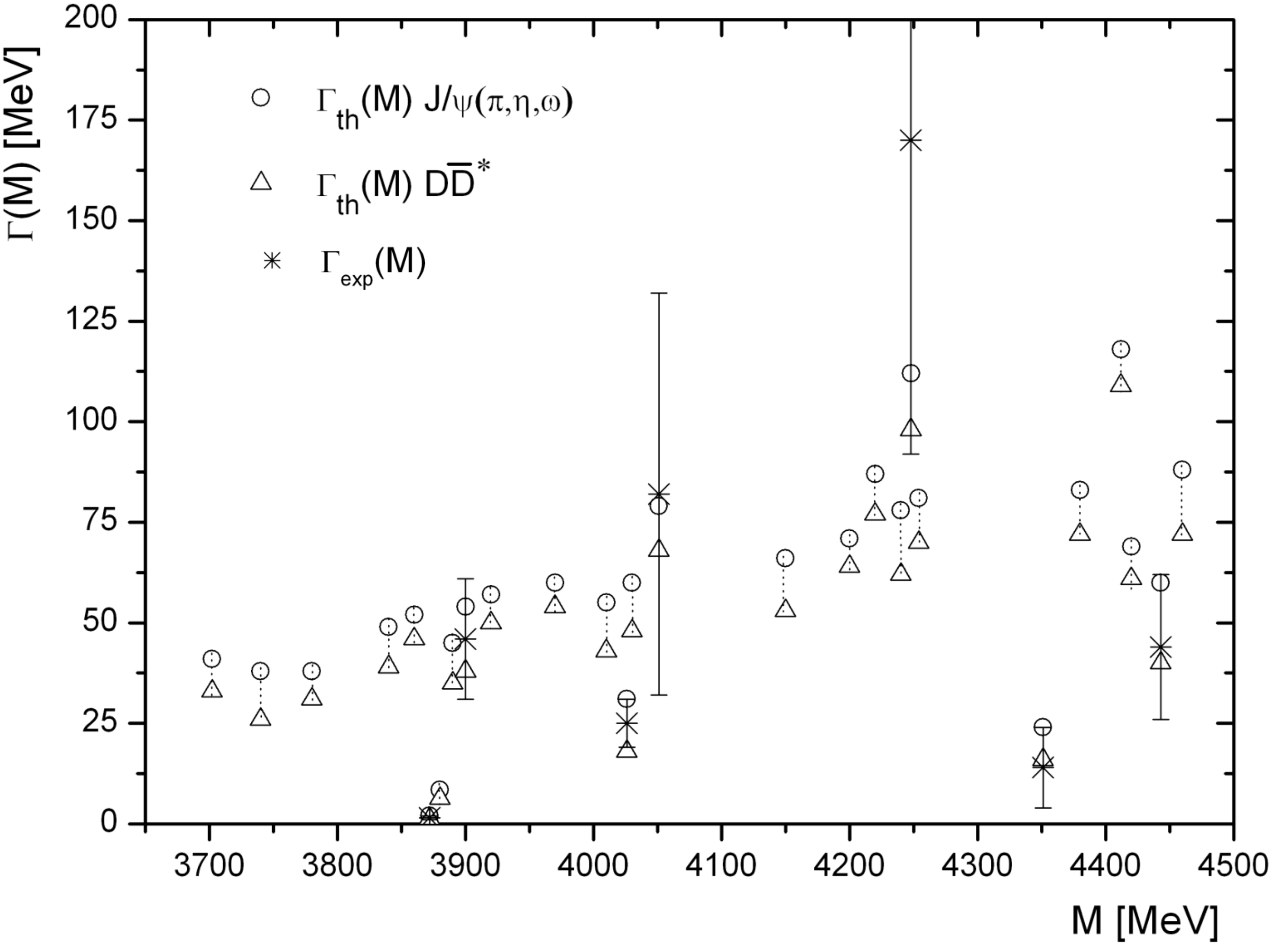
where

where $F_L(r)$ – is the regular decision in the $V_2(r)$ potential, normalized on the energy delta-function; $\phi_L(r)$ – normalized wave function of the resonance state. This wave function transforms into irregular decision in the $V_2(r)$ potential far away from the internal turning point.

The integral can be estimated with the well known approximately methods: for example, the saddle-point technique or the other numerical method.

THE WIDTHS OF TRIPLET $^3S_1$ CHARMONIUM STATES





Γ(M) [MeV]
M [MeV]
Γ_{th}(M) J/ψ(π,η,ω)
Γ_{th}(M) $D\overline{D}^*$
Γ_{exp}(M)
200
175
150
125
100
75
50
25
0
3700
3800
3900
4000
4100
4200
4300
4400
4500

PHYSICS WITH PROTON - PROTON COLLISIONS:

• search for the bound states with gluonic degrees of freedom: glueballs and hybrids of the type gg, ggg, $\overline{Q}Qg$, Q^3g in mass range from 1.3 to 5.0 GeV. Especially pay attention at the states $\overline{s}sg$, $\overline{c}cg$ in mass range from 1.8 – 5.0 GeV.

• charmonium-like spectroscopy $\overline{c}c$, *i.e.* $pp \to \overline{c}c\, pp$ (threshold $\sqrt{s} \approx 5$ GeV)

• spectroscopy of heavy baryons with strangeness, charm and beauty:

$$\Omega^0_c, \Xi_c, \Xi'_c, \Xi^+_{cc}, \Omega^+_{cc}, \Sigma^*_b, \Omega^-_b, \Xi^0_b, \Xi^-_b.$$

$$pp \to \Lambda_c X;\ pp \to \Lambda_c pX;\ pp \to \Lambda_c pD_s \qquad pp \to \Lambda_b X,\ pp \to \Lambda_b pX;\ pp \to \Lambda_b pB_s$$

• study of the hidden flavor component in nucleons and in light unflavored mesons such as $\eta, \eta', h, h', \omega, \varphi, f, f'$.

• search for exotic heavy quark resonances near the charm and bottom thresholds.

• *D*-meson spectroscopy and *D*-meson interactions: *D*-meson in pairs and rare *D*-meson decays to study the physics of electroweak processes to check the predictions of the Standard Model and the processes beyond it.

-*CP*-violation - Flavour mixing -Rare decays

Running conditions

1. $p+p$ at $\sqrt{s} = 25$ GeV

2. Luminosity $L = 10^{29}\ cm^{-2}c^{-1} - 10^{31}\ cm^{-2}c^{-1}$

3. Running time 10 weeks:
integrated luminosity $L_{int} = 604.8\ nb^{-1} - 60.48\ pb^{-1}$

Expectations for J/ψ

1. X-section $\sigma_{J/\psi}$ from Pythia6 41.5 nb (factor ~2 below experiment)

2. Decay channel $J/\psi \rightarrow e^{+}e^{-}$ (branching ratio ~6%)

3. Statistics: $N_{J/\psi} = L_{int} \cdot \sigma_{J/\psi} \cdot Br_{J/\psi \rightarrow e+e-} \cdot Eff_{\Delta\eta = \pm 1,5} =$
$604.8 \cdot 41.5 \cdot 0.06 \cdot 0.8 = 1205$

Y(4260) state

1. X-section in Pythia6 for heavy flavours with default PDF and $Y(4260) \equiv \chi_{c2}(4260)$ is 81.3 nb

2. X-section for Y(4260) 9.1 nb

X(3872) state

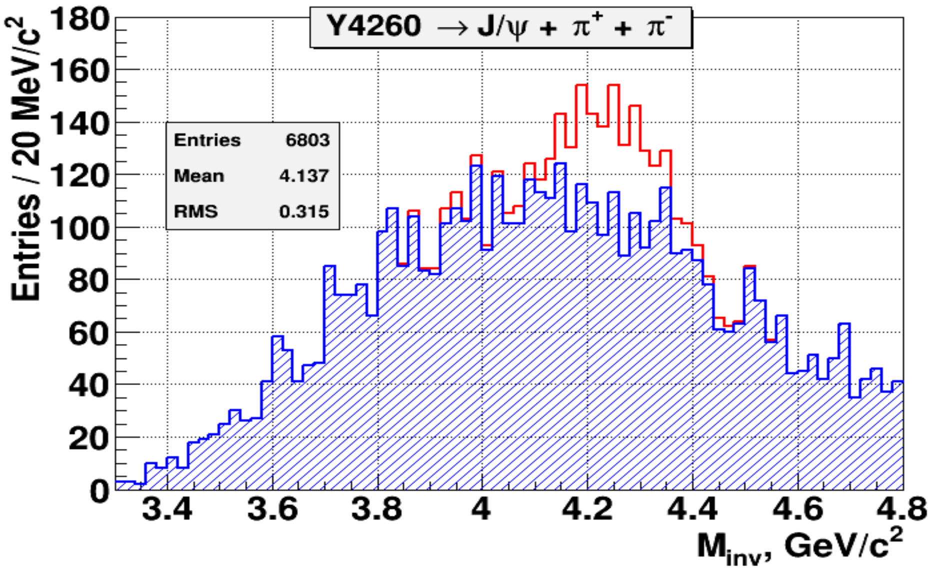
1. X-section in Pythia6 for heavy flavours with default PDF and $X(3872) \equiv \chi_{c2}(3872)$ is 92.9 nb

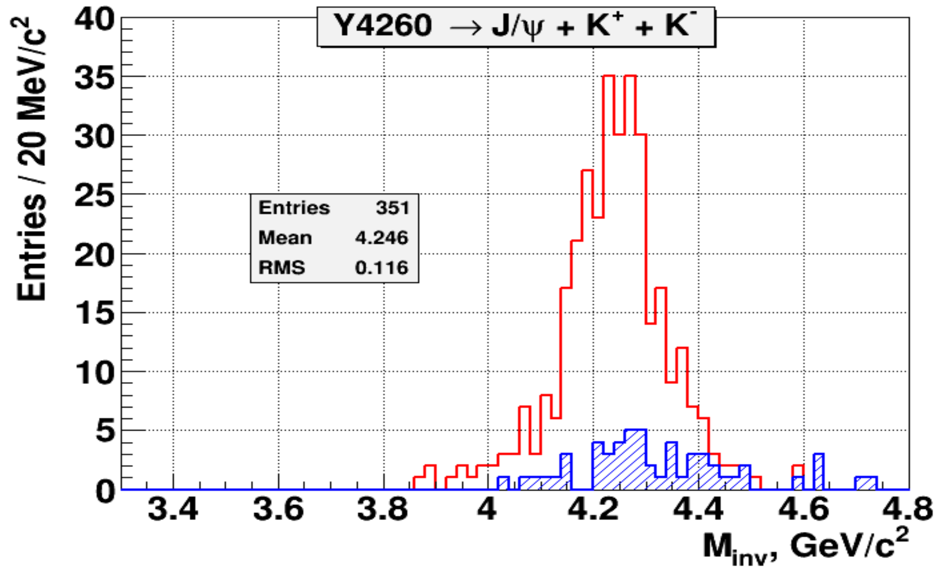
2. X-section for X(3872) 20.9 nb

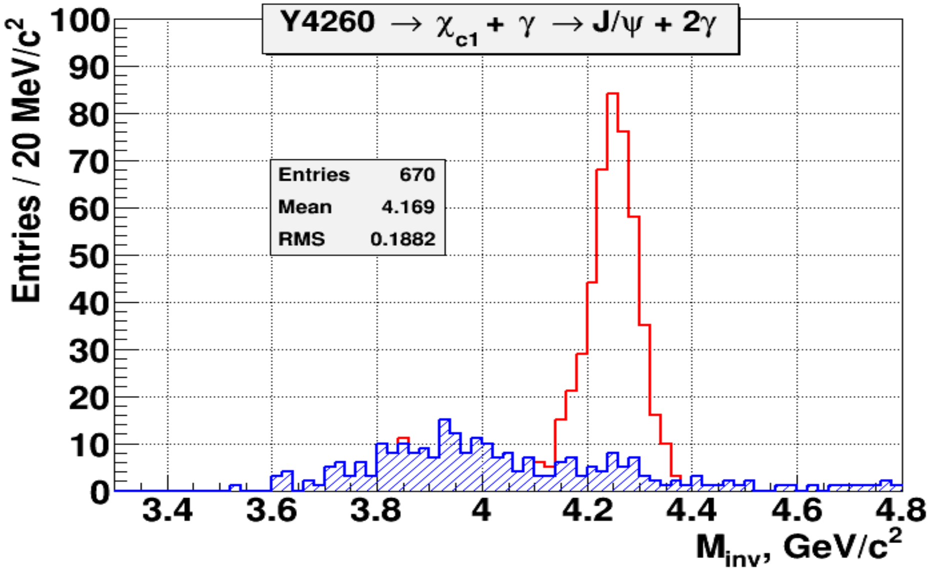
3. X(3872) decay table as for $\psi(2S)$:

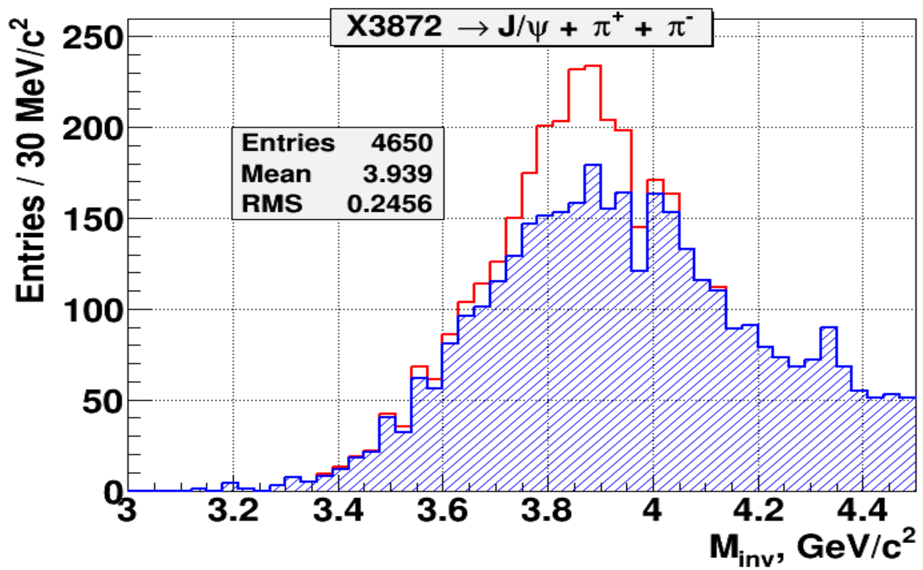
   $Br\ (X3872 \rightarrow J/\psi\ \pi+\pi-) = 32.4\%$
   $Br\ (X3872 \rightarrow e+e-\ \pi+\pi-) = 1.9\% \rightarrow$ X-section = 0.42 nb
   1000 events for 10 weeks: $L = 3.9 \cdot 10^{29}\ cm^{-2}s^{-1}$

Decays of charmonium-like states









Summary

- Many observed states remain puzzling and can not be explained for many years. This stimulates and motivates for new searches and ideas. New theoretical models are needed to obtain the nature of charmonium-like states.
- Different charmonium-like states are expected to exist in the framework of the proposed combined approach based on quarkonium potential model and confinement model.
- The most promising decay channels of charmonium-like states have been analyzed. It is expected that charge / neutral tetraquarks with hidden charm must have neutral / charge partners with mass values which differ by few tens of MeV.
- Using the integral approach for the hadron resonance decay, the widths of the expected states of charmonium & tetraquarks were calculated; they turn out to be relatively narrow; most of them are of order of several tens of MeV.
- NICA & FAIR can provide important complimentary information and new discoveries. Look for different charmonium-like states (conventional and exotic) in *pp* collisions seems promising to obtain complementary results to the ones from e^+e^- and $\bar{p}p$ interactions. If *pp* program will be further developed, measurements of charmonium-like states can be considered as one of the "pillars" of *pp* program at NICA.

PERSECTIVES AND FUTURE PLANS

- *D*-meson spectroscopy:

-*CP*-violation

-Flavour mixing

-Rare decays

- Baryon spectroscopy:

-Strange baryons

-Charmed baryons

! • Physics simulation (is in progress nowadays)

THANK YOU!